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A METHOD FOR IDENTIFICATION OF NON-COAXIALITY IN ENGINE SHAFT LINES OF A SELECTED TYPE OF NAVAL SHIPS

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ABSTRACT

A correctly designed machine is characteristic of low vibration values. However wear processes occur during its operation. They are accompanied by a lack of balance of its rotating parts and elements, which results in non-coaxiality of shafts. For this reason energy and dynamic load resulting from machine vibrations grows. In this case cause and effect are mutually connected by feedback, that inevitably leads to occurrence of a failure. This paper presents results of investigations carried out on the basis of vibration analysis of propulsion systems installed on 207P minesweepers. In view of specific features of their operation it is very important to ensure high level of reliability for them. For this reason was done an attempt to develop a method intended for identifying non-coaxiality of shaft line systems of engines propelling the ships. 16 characteristic features of recorded vibration signals were selected. As any of them has not satisfied criteria assigned to features which unambiguously determine state of reliability of shaft line systems, the investigations have been continued and as a result a novel method for non-coaxiality identification was proposed. The method consists in determining unserviceability clusters and assumes that characteristic features are of a concentrated character. This way a non-coaxiality of main engine shaft lines of 207P minesweepers could be detected. This paper presents the proposed method and results of its application to the case in question.

Keywords: shaft lines, vibrations, non-coaxiality identification , signal analysis.

INTRODUCTION

During its work any engineering system fulfills tasks for which it was designed and built. Their fulfillment results in change of values of the system's features [1,5]. The changes are caused by impact of factors associated with wear processes [8] which may be divided in two groups: that independent on system's operation and that dependent on it [16]. Based on analysis of subject-matter literature it was found that the earliest symptoms of change in dynamics of rotary systems may be detected by measuring vibration level and temperature of a system. Shaft line non-coaxiality which appears during operation of a system, is demonstrated by rise in quantity of machine vibration parameters [2,3,4,10,11,12,13,20,22], therefore a method for detecting non-coaxiality by analyzing vibration of main engine shaft line has been proposed.

For developing the method in question the investigations were conducted in actual service conditions of the considered propulsion systems , which, based on results of measurements, were verified by means of R2 coefficient and model simulation results [7]. The tests were performed on the basis of assessment of selected parameters of propulsion systems on 207P minesweepers (whose image is shown in Fig. 1.)

The investigations have been focused on ships of this type produced in Poland in the 1980s and 1991. They were modernized between the years 1989 and 1994 however main elements of their propulsion systems have been left unchanged. 17 units of this type were built in total. All of them are still in service. The investigations were carried out on four units in similar conditions, i.e. in a sea state not higher than 20 B (Fig.2), and at engine room temperature equal to about 40° C.

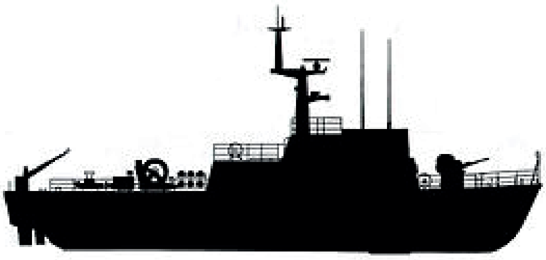

Fig. 1. A profile of 207P minesweeper

Fig. 2. Object of the conducted investigations [21]

Every unit was fitted with two propulsion systems consisted of: a propulsion engine of the rated power output of 73 kW at the rated rotational speed of 1550 rpm, a hydrokinetic coupling of the rated slip of 2% and the slip control range from 2 to 98 %, a reversing reduction gear of 3.5:1 reduction ratio and a thrust bearing fitted with three rolling bearings. The systems were symmetrically installed in ship's watertight compartments. The starboard engine is dextrorotatory and backboard one – laevorotatory. All main shaft line systems were in serviceability state, except of one which was unserviceable as a result of its non-coaxiality.

THE INVESTIGATIONS PERFORMED ON SHIPS IN OPERATION

Main engine shaft vibrations were measured in 6 measurement points for each of the propulsion system, which were located on: the engine bed plate, power consumer facing engine shaft end, hydrokinetic coupling, bearing at input to reversing reduction gear, bearing at output from the gear, and the thrust bearing (Fig. 3).

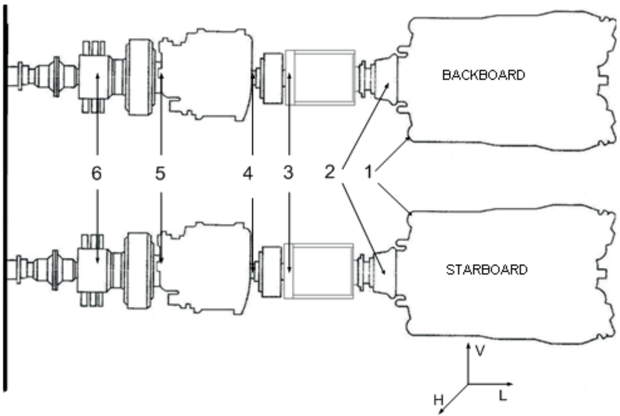

Fig. 3. Arrangement of measurement points on the analyzed propulsion systems: 1 – engine bed plate; 2 – power consumer facing engine shaft end; 3 – hydrokinetic coupling; 4 – bearing at input to reversing reduction gear; 5 – bearing at output from the gear; 6 –thrust bearing

Identical acceleration measuring instruments (4514B B&K) were used for measurements. They were mounted on mutually perpendicular axes. Since it was impossible to use threaded joints the transducers were glued directly to the tested parts. Measuring channels were calibrated before and after each measurement session. All the procedure was conducted in compliance with [17] and the industrial branch standard [15]. All recorded signals were synchronized by means of a four-channel measurement cassette [15].

The vibrations were recorded in 3.2 kHz frequency band at 8192 Hz sampling frequency.

As already mentioned, the signals were taken on four investigated objects comprising two propulsion shaft lines each. They were recorded separately at 4 rotational speeds (850 rpm, 1100 rpm, 1300 rpm and 1500 rpm) in three mutually perpendicular directions. Measurement results were saved as cvs files. Each of the files comprised values of vibration parameters for a given ship, shaft line system, measurement point and rotational speed. As a result of the conducted investigations 150 files were obtained after elimination, from the analysis, of those comprising erroneous data [7].

Because the vibrations were recorded on different objects and by different measurement teams, the files differed somewhat to each other as far as their names, lengths and contents have been concerned [14]. For this reason the files were saved in one folder and divided in such a way as to get vibration values for each direction written separately, hence to make it possible to process all the saved data automatically. Simultaneously, folder names were changed, according to the scheme (1), by assigning numbers to starboard measurement points in the same way as to respective backboard ones.

ssss_bbb_pp_oooo_d.csv (1)

where:
sssss – ship's name written in 5 positions (goplo, mamry, mamr2, sniar);
bbb – shaft line system written in 3 positions (llw, plw);
pp – measurement point number written in 2 positions (01,02,03,04,05,06);
oooo –rotational speed written in 4 positions (0850, 1100, 1300, 1500);
d – direction symbol written in 1 position (v, h, l).

Next, the files were split in such way as each of them to contain 1024 measured values. After analysis of the obtained files it was found that the last files achieved as a result of splitting the initial files into groups containing 1024 measurements each, comprised less measurements. However the files were not eliminated from further analysis. Finally, 22680 files were obtained. For every combination: measurement point – vibration axis – rotational speed (i.e. PDS), the set contained 252 files for main engine shaft lines in serviceability state and 63 files for shaft lines in unserviceability state. Fig. 3 and 4 present exemplary values written in the obtained files. In the figures, on their horizontal axes, are given successive numbers of measurements whose distance in time results from sampling frequency and amounts to 1/8192 s.

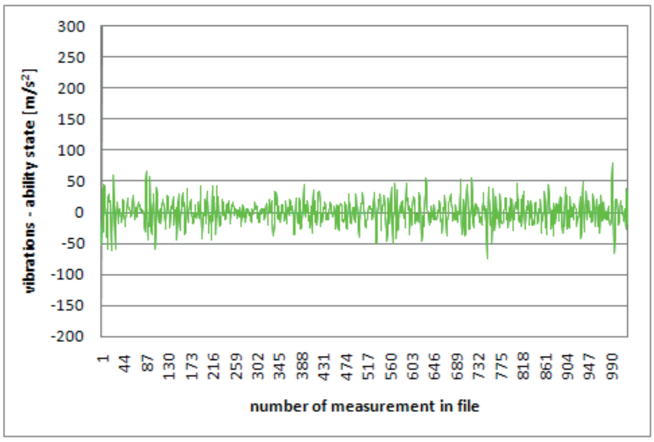

Fig. 4. Exemplary run of main engine shaft line vibrations - serviceability state

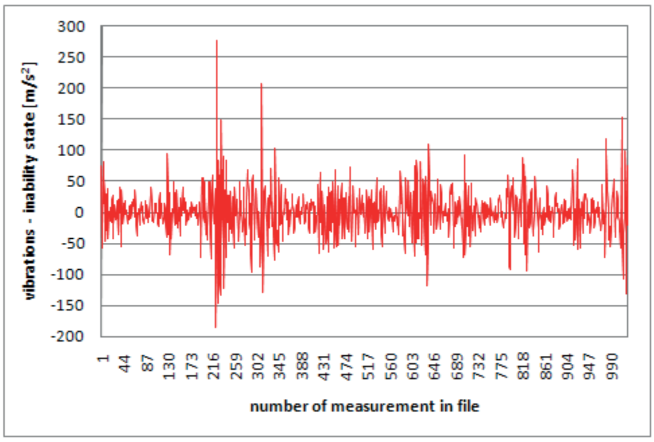

Fig. 5. Exemplary run of main engine shaft line vibrations - unserviceability state

ANALYSIS OF THE OBTAINED DATA

In the next phase of the investigations it was stated that vibration values contained in each file may be considered discrete signals presented in time domain. For each signal denoted as vsi, the following characteristics ($CH(vs_i)$) were calculated [9,18]:

- integral of the signal – $I(vs_i)$,
- mean value of the signal – $M(vs_i)$,
- energy of the signal – $E(vs_i)$,
- mean power of the signal– $P(vs_i)$,
- 1st order moment of the signal – $M1'(vs_i)$,
- 2nd order moment of the signal – $M2'(vs_i)$,
- 1st order central moment of the signal – $C1(vs_i)$,
- 2nd order central moment of the signal – $C2(vs_i)$,
- 1st order normalized moment of the signal – $N1(vs_i)$,
- 2nd order normalized moment of the signal – $N2(vs_i)$,
- 1st order normalized central moment of the signal– $NC1(vs_i)$,
- 2nd order normalized central moment of the signal - $NC2(vs_i)$,
- abscissa of signal square gravity centre -$G(vs_i)$,
- signal square variance– $V(vs_i)$,
- signal equivalent diameter– $ED(vs_i)$.

The signals take non-zero values only within a definite segment of time axis, therefore they are pulse signals [23]. Additionally, after analysis of the calculated characteristics it was stated that the signals belong to the category of pulse signals of a limited energy. Therefore they may be considered functions of the space $L2(t_0,t_k)$, where t_0 is a time corresponding to the first measurement in a file, and tk – that corresponding to the last measurement in a file. The space is defined as a pulse signal space of limited energy [19]. By extending it with norm, addition and scalar multiplication Hilbert normalized space is formed [6]. By making use of its properties it was determined that normalized correlation coefficient is a measure of similarity for pulse signals.

Value of the normalized correlation coefficient depends on shift along time axis of signals, relative to each other. In the case of recorded signals a signal shift should not be of importance. In view of that, value of normalized mutual correlation function of signals was assumed to be similarity measure for considered signals.

Time runs of vibration values are actual signals. In case of such signals a coupled signal is equal to initial one. Therefore the normalized mutual correlation function of time runs of recorded vibrations (α') takes the following form [18]:

$$\alpha'_{vs_i,vs_j}(\tau)=\frac{\left(\int_0^{\max(t_k)} vs_i(t)\Big|_{t_0}^{t_k}\cdot vs_j(t-\tau)\Big|_{t_0}^{t_k}dt\right)^2}{\int_0^{\max(t_k)} vs_i(t)\Big|_{t_0}^{t_k}{}^2\,dt\cdot\int_0^{\max(t_k)} vs_j(t)\Big|_{t_0}^{t_k}{}^2\,dt} \qquad (2)$$

The selected similarity measure of signals determines distance between runs in the space L2 depending on their relative shift along time axis. In the case when determination of the highest similarity of signals irrespective to their time shift is the aim of research , maximum value of the normalized mutual correlation function should be taken as a signal similarity measure. Considering the recorded time runs one aims at determination of a measure of their distance in the space L2, but such measure should be increasing along with signal distance increasing. For this reason the following expression was assumed to be the signal distance measure (3):

$$\delta(vs_i,vs_j)=1-\max(\alpha'_{vs_i,vs_j}(\tau\in[-t_k,t_k])) \qquad (3)$$

where:
$\delta(vs_i,vs_j)$ - distance between the signals vs_i and vs_j in the space L2.

In order to apply the above presented measure to recorded runs, for every PDS group a single file was selected to serve as a reference signal for the whole group. On this basis distance between a given signal and its reference signal was calculated from Eq. (3), as well as mean value and standard deviation for every so - defined characteristic for each of the signal groups, separately.

Moreover it was found that the characteristic is concentrated if standard deviation of values of the characteristic group of signals is lower than 15% of the mean value, (4).

$$CH_{CON}\Leftrightarrow\sigma_{CH(PDS)}\le\overline{CH}(PDS)\cdot 0.15 \qquad (4)$$

where :
CH_{CON} – concentrated characteristic;
$\sigma_{CH(PDS)}$– standard deviation of the characteristic CH calculated for the signal group PDS;
$\overline{CH}(PDS)$ – mean value of the characteristic CH calculated for the signal group PDS.

It was also assumed that, if the signal characteristic in question has to be considered that which unambiguously determines reliability state of shaft line system, then it should be a concentrated characteristic, and absolute value of difference of mean values of signal distance in the group PDS for shaft lines in serviceability state and mean values of signal distance in the group PRS for shaft lines in non-serviceability state, should be greater than sum of standard deviations of signals for these two groups. The characteristic is considered unambiguous (5).

$$CH_{UE} \Leftrightarrow \{CH \in CH_{CON} \wedge \\ \sigma_{CH(PDS_{IA})} + \sigma_{CH(PDS_A)} \le \left|\overline{CH}(PDS_{IA}) - \overline{CH}(PDS_A)\right|\} \tag{5}$$

where:

CH_{UE} – unambiguous characteristic;

CH_{CON} – concentrated characteristic;

$\sigma_{CH(PDS)}$ – standard deviation of the characteristic CH calculated from PDS group of signals;

$\overline{CH}(PDS)$ – mean value of the characteristic CH calculated from PDS group of signals;

PDS_{IA} – PDS group of signals recorded in main engine shaft line system in unserviceability state

PDS_A – PDS group of signals recorded in main engine shaft line system in serviceability state .

Number of groups of signals satisfying condition of concentration and number of group of signals satisfying condition of unambiguity were determined on the basis of calculation results. Tab. 1 contains the results.

Tab. 1. Concentration and unambiguity of characteristics

Characteristic	Number of PDS groups satisfying condition of concentration (%)	Number of PDS groups not satisfying condition of unambiguity (%)
Integral	0	1,47
Mean value	0	1,47
Energy	76,47	58,82
Mean power	76,47	58,82
1st order moment	0	0
2nd order moment	0	0
1st order central moment	0	0
2nd order central moment	0	0
1st order normalized moment	0	0
2nd order normalized moment	0	0
1st order normalized central moment	1,47	0
2nd order normalized central moment	0	0
abscissa of signal square gravity centre	98,52	0
Signal square variance	76,47	0
Śignal equivalent diameter	0	0
Distance from reference signal	89,7	0

METHOD FOR NON-COAXIALITY IDENTIFICATION

On the basis of the values presented in Tab. 1 it was found out that among 16 analyzed characteristics only energy and mean power of signal satisfied conditions of concentration and unambiguity. Unfortunately, they satisfy the conditions only partially and therefore they cannot be the only criteria for identification of non-coaxiality of main engine shaft line systems as far as their qualitative, numerically expressed assessment at a given time instance t, is concerned [14].

Analysis of the values contained in Tab. 1 made it possible to distinguish the characteristics which satisfy condition of concentration in a relatively high degree. These are: signal energy, mean power of signal, abscissa of signal square gravity centre, signal square variance and distance from reference signal.

The distinguished characteristics were used for formulation of a method for identification of non-coaxiality in main engine shaft line systems. To this end the files obtained as a result of operational investigations were divided into two groups. The first of them comprised 14212 files (11356 for shaft line systems in serviceability state and 2856 for shaft line systems in unserviceability state) and the second – comprising 7072 files (5644 for shaft line systems in serviceability state and 1428 for shaft line systems in unserviceability state). The first group was used for determination of central point and radius of five-dimensional clusters of serviceability and unserviceability states identified for each of the PDS groups, separately. Coordinates of central points of the clusters were calculated according to the expression (6), and their radiuses – on the basis of the relation (7):

$$CCP_R = (\overline{E}, \overline{P}, \overline{G}, \overline{V}, \overline{\delta}) \tag{6}$$

where :

CCP_R – central point of the cluster of the reliability state R for a given PDS group;

R – reliability state equivalent to serviceability state and unserviceability state;

$\overline{E}$ – mean value of signal energy calculated for a given PDS group for the reliability state R;

$\overline{P}$ – mean value of mean signal power calculated for a given PDS group for the reliability state R;

$\overline{G}$ – mean value of abscissa of signal square gravity centre calculated for a given PDS group for the reliability state R;

$\overline{V}$ – mean value of square variance calculated for a given PDS group for the reliability state R;

$\overline{\delta}$ – mean value of distance from reference signal calculated for a given PDS group for the reliability state R.

$$CR_R = \underset{vs_i \in PDS_R}{MAX}\left(\sqrt{\sum_{j=1}^{5}(\overline{CH_j} - CH_j(vs_i))^2}\right) \tag{7}$$

where:

CR_R – cluster radius for a given PDS group for the reliability state R;

R – reliability state equivalent to serviceability state and non-serviceability state;

$\overline{CH_j}$ – mean value of the characteristic j calculated for the reliability state R for a given PDS group;

$CH_j(vs_i)$ – the characteristic j calculated for the signal vs_i;

vs_i – a signal which belongs to a given PDS group of the reliability states R;

j – a characteristic which takes values of : signal energy , its mean power, abscissa of signal square gravity centre, signal square variance or distance from reference signal.

Next, the second-set signals were analyzed. Such signal was defined as that which belongs to serviceability state cluster, if distance between the signal and serviceability cluster central point , calculated from the relation (8), satisfied the condition (9).

$$\delta(CCP_A, vs_i) = \sqrt{\sum_{j=1}^{5}(CH_j(CCP_A) - CH_j(vs_i))^2} \quad (8)$$

where:

$\delta(CCP_A, vs_i)$– signal distance from central point of serviceability state cluster;

CCPA – serviceability state cluster central point;

vs_i – a signal which belongs to a given PDS group of serviceability state;

CHj(CCP_A) – value of the characteristic CHj of the coordinate CCP_A;

CHj(vs_i) – the characteristic j calculated for the signal vs_i;

j – a characteristic which takes values of: signal energy, its mean power, abscissa of signal square gravity centre, signal square variance or distance from reference signal.

$$\delta(CCP_A, vs_i) \le CR_A \quad (9)$$

where:

CRA – radius of serviceability state cluster;

$\delta(CCP_A, vs_i)$ – distance between a signal and central point of serviceability state cluster.

Similarly, such signal was defined as that belonging to unserviceability state cluster, if distance between the signal and unserviceability cluster central point, calculated from the relation (10), satisfied the condition (11):

$$\delta(CCP_{IA}, vs_i) = \sqrt{\sum_{j=1}^{5}(CH_j(CCP_{IA}) - CH_j(vs_i))^2} \quad (10)$$

where:

$\delta(CCP_{IA}, vs_i)$– signal distance from central point of unserviceability state cluster;

CCP_{IA} – central point of unserviceability state cluster;

vs_i – a signal which belongs to a given PDS group of unserviceability state;

CHj(CCP_{IA})- a value of the characteristic CHj of the coordinate CCP_{IA};

CHj(vs_i) - the characteristic j calculated for the signal vs_i;

j – a characteristic which takes values of : signal energy, its mean power, abscissa of signal square gravity centre, signal square variance or distance from reference signal.

$$\delta(CCP_{IA}, vs_i) \le CR_{IA} \quad (11)$$

where :

CR_{IA} – radius of unserviceability state cluster;

$\delta(CCP_{IA}, vs_i)$ – distance between a signal and central point of unserviceability state cluster.

A signal was taken as that confirming serviceability state of main engine shaft line system if it belonged to serviceability state cluster but not to unserviceability state cluster.

According to the same principle a signal was regarded as that confirming unserviceability state of main engine shaft line system if it belonged to unserviceability state cluster but not to serviceability state cluster.

If a signal belonged neither to serviceability state cluster nor to unserviceability state cluster or it belonged to both the clusters simultaneously, then distances between signal in question and central points of the clusters were analyzed (8), (10). A signal was regarded as that confirming serviceability state of main engine shaft line system if the calculated distances satisfied conditions defined by the formula (12). Otherwise signal in question was not regarded as that confirming occurrence of unserviceability state.

$$\delta(CCP_A, vs_i) < \delta(CCP_{IA}, vs_i) \quad (12)$$

where :

$\delta(CCP_A, vs_i)$ – distance between a signal and central point of serviceability state cluster;

$\delta(CCP_{IA}, vs_i)$ – distance between a signal and central point of unserviceability state cluster.

Tab. 2 shows results of the examination of the second set of signals.

Tab. 2. Effectiveness of the method for non-coaxiality identification

	Number of investigated signals	Number of detected signals confirming serviceability state of shaft line systems	umber of detected ignals confirming nserviceability state of haft line systems
Signals taken from shaft line system in serviceability state	5712	3738 (65%)	974 (35%)
Signals taken from shaft line system in unserviceability state	1428	92 (6%)	336 (94%)

On the basis of analysis of values comprised in Tab. 2 it was found out that the proposed method may reach very high effectiveness in case of the signals recorded in main engine shaft line systems being in unserviceability state. As far as the signals recorded in main engine shaft line systems being in serviceability state are concerned, precision of their identification is lower. Therefore it is suggested to apply the method in question to the assessing of occurrence probability of non-coaxiality in main engine shaft line systems in unserviceability state. The indicated signals should undergo further analyses to exclude those recorded in main engine shaft line systems in serviceability state.

CONCLUSIONS

On the basis of results of the presented investigations it was concluded that :

- out of 16 characteristic features of recorded signals, only energy and mean power of signal satisfies conditions of concentration and unambiguity;
- energy and mean power of signal satisfies the conditions only partially hence they cannot be the only criteria for identification of occurrence of non-coaxiality in main engine shaft line systems;

- signal energy, mean power and abscissa of signal square gravity centre , signal square variance and distance from reference signal represent concentrated features and may be used for developing a method for identification of non-coaxiality in main engine shaft line systems;
- effectiveness of the developed method is satisfactory as it amounts to 65% in case of the signals recorded in shaft line systems in serviceability state and to 94% in case of the signals recorded in shaft line systems in unserviceability state;
- it is recommended to apply the method in question to detection of non-coaxiality in main engine shaft line systems;
- the indicated signals should be further analyzed in order to exclude those recorded in main engine shaft line systems being in serviceability state.

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